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Influence of the maximum flow ramping rates on the water value

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Abstract

This paper presents a study on the influence of maximum ramping rates (ρ) on the water values of a real hydropower plant. For this purpose, a master-slave algorithm, based on stochastic dynamic programming (SDP) and mixed integer linear programming (MILP), is used. The master module, based on SDP, has a 1-year planning period with weekly time steps and considers 3 state variables: stored volume of water in the reservoir at the beginning of each week; weekly water inflow; and average weekly energy price. The slave module, based on MILP, has a 1-week planning period with hourly time steps and considers: maximum legal and minimum technical storage capacities; maximum and minimum technical stored volumes for power generation; maximum and minimum flows released through the hydro units, the bottom outlets and the spillways according to the stored volume; one different power-discharge piecewise linear non-concave curve, as a function of the initial and estimated final stored volumes; start-up and shut-down costs of the hydro units; wear and tear costs of the hydro units caused by power variations; hourly evaporation losses according to the stored volume; hourly water inflows and energy prices; and up and down ρ. The results indicate that the water values of the hydropower plant are very sensitive to the presence of ρ; especially during the months with low water inflows. Water values decrease quadratically when increasing ρ.

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Keywords: Maximum ramping rates; Mixed integer linear programming; Stochastic dynamic programming; Water value

1. Introduction

The United Nations [1] has exhorted that energy must be produced in a sustainable way. Probably because of this global need and especially due to its high efficiency, reliability and versatility, hydroelectricity has become the fourth source of primary energy in the world and the first one among renewable energies [2]. Unfortunately, this sort

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Nomenclature

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a	Weekly water inflow of the subproblem.
b	Average weekly energy price of the subproblem.
c	Reservoir segment for the maximum plant flow.
i	Initial stored water volume of the subproblem.
k	Week of the year.
l	Final stored water volume of the subproblem.
j	Segment of the water value curve.
s	Segment of the power-discharge curve.
s^u	First segment of the power-discharge curve of the u-th hydro unit in ascending order of flow.
t	Hour within the week.
u	Hydro unit of the plant.
x	Next weekly water inflow of the subproblem.
y	Next average weekly energy price of the subproblem.

Constants

CF^1	Conversion factor [0.0036Mm^3/h/m^3/s].
CF^2	Conversion factor [1/0.6048Mm^3/week/m^3/s].

Parameters

α	Wear and tear costs of hydro units due to variations in the generated power.
β	Shut-down and start-up costs for hydro units.
γ	Virtual cost of outlets and spillways due to variations in the released flow.
$\varepsilon_k^{a,x}$	Transition probability of the inflow at the week k+1 is x given at the week k the inflow was a.
$\varepsilon_k^{b,y}$	Transition probability of the average price at the week k+1 is y given at the week k the average price was b
π_t	Energy price during the hour t.
E_k	Evaporation rate during the week k.
e^s	Maximum flow of the s-th segment of the power-discharge curve.
KE^1,KE^2	Coefficients of the linear approximation of the surface-storage reservoir curve.
KO^1,KO^2	Coefficients of the linear approximation of the maximum outlet flow-storage reservoir curve.
KS	Coefficient of the linear approximation of the maximum spillway flow-storage reservoir curve.
j^{max}	Total number of water value segments.
p^{min}	Minimum power output of the power-discharge curve.
$Q^{max,c}$	Maximum plant flow of the c-th reservoir segment for the maximum plant flow.
Q^{max}	Maximum plant flow.
Q^{min}	Minimum plant flow.
Q^u	Plant flow above which the u-th hydro unit starts-up.
RR^{down}	Down ρ.
RR^{up}	Up ρ.
r^s	Slope of the s-th segment of the power-discharge curve.
u^{max}	Total number of hydro units of the plant.
V^{dead}	Dead reservoir volume (stored volume below the bottom outlets).
V_k^i	Stored volume i at the beginning of the week k
V_k^{legal}	Maximum legal stored volume at the end of the week k.
V^{max}	Maximum technical stored volume.
VQ^c	Reservoir volume of the c-th reservoir segment for the maximum plant flow.
VS	Stored volume from which the spillways can operate.
VWV^j	Stored volume of the j-th segment of the water value curve.
w_t	Water inflow to the reservoir during the hour t.
$WV_k^{j,a,b}$	Water value of the j-th reservoir segment at the end of the week k given the inflow a and price b.

Sets

Ω_k	Feasible decisions within the discretization of the state variables during the week k.
C	Reservoir segments for the maximum plant flow.
J	Segments of the water value curve.
K	Weeks of the year.
S	Segments of the power-discharge curve.
T	Hours of the week.

Binary variables

off_t^u	= 1 if the u-th hydro unit is shut-down during the hour t.
on_t^u	= 1 if the u-th hydro unit is started-up during the hour t.
o_t^u	= 1 if the u-th hydro unit is on-line during the hour t.
sp_t	= 1 if the stored volume is above VS during the hour t.
vq_t^c	= 1 if the stored volume is above of the c-th reservoir segment for the maximum plant flow during the hour t.
wv^j	= 1 if the stored volume is within the j-th segment of the water value curve.

Non-negative variables

e_t	Flow of evaporation during the hour t.
p_t	Generated power during the hour t.
p_t^{dec}	Decrease in generated power between the hours t and t+1.
p_t^{inc}	Increase in generated power between the hours t and t+1.
q_t	Plant flow during the hour t.
q_t^s	Plant flow corresponding to the s-th segment of the power-discharge curve during the hour t.
qo_t	Released flow through the outlets during the hour t.
qs_t	Released flow through the spillways during the hour t.
qos_t^{dec}	Decrease in released flow through the bottom outlets and the spillways between the hours t and t+1.
qos_t^{inc}	Increase in released flow through the bottom outlets and the spillways between the hours t and t+1.
v_t	Stored volume at the end of the hour t.
vas_t	Stored volume at the end of the hour t above the spillways.
vbs_t	Stored volume at the end of the hour t below the spillways.
vwv^j	Stored volume in the j-th segment of the water value curve at the end of the subproblem.
$Z_k^{i,a,b}$	Optimum cumulative revenue at the stored volume i, inflow a and price b from the week k to the end of the year.
$z_k^{i,a,b,l}$	Revenue corresponding to the decision to go from the stored volume i, inflow a and price b to the stored volume l during the week k.

of power generation can yield undesirable effects on the ecosystems where it is produced [3] and, therefore, many countries have imposed [4] or are developing [5] specific environmental policies to protect rivers from hydropower effects. One of the most common expressions of these policies consists in the imposition of maximum flow ramping rates (ρ) which, on the one hand, increase the number of operating hours of the hydropower plant and, on the other hand, reduce the producer's revenue and the number of start-ups and shut-downs of the hydro units [6].

The United Nations [1] has also recognized that water has an economic value in all its competing uses. In the case of a hydropower producer in a competitive electricity market, this value can be defined in several ways but for the purpose of the present study it has been chosen the profit-based value described by Reneses et al. [7], i.e.: variation of the company's profit with respect to its available hydraulic resources. As first pointed out by Stage and Larsson [8], the so-called marginal water value depends on the stored water volume and the time of the year and, as Fosso and Belsnes [9] stated, it is an important interface between the long- and short-term scheduling models.

Nowadays there is a plethora of literature on the value of water in hydropower reservoirs and it is not uncommon to find algorithms capable of dealing with ρ but, to the best of our knowledge, there is no previous work where the influence of the said constraint on the water value has been analysed. This is precisely the purpose of the present study.

For this purpose, a *master-slave algorithm* similar to the one proposed by Abgottspon and Andersson [10], has been applied to determine the water values of a real hydropower plant with annual regulation capacity, which participates in the Spanish day-ahead electricity market. As in [10], the master-slave algorithm is based on *stochastic dynamic programming* (SDP) and *mixed integer linear programming* (MILP). All the results obtained by the slave module are recalculated by the master module by using the real plant generation characteristic, obtained from the turbine hill curves, the height-volume curve of the reservoir, the friction head losses coefficients in the conduits and the water elevation curve in the tailrace area. *Linear programming* and *dynamic programming* are the most popular techniques applied to determine the optimal operation of reservoir systems [11]. Furthermore, hybrid optimisation models that combine and take advantage of the best of both techniques have been used with considerable success [10,12,13].

The study is organised as follows. In Sec. 2 and 3, the master and slave modules are described. In Sec. 4, the case study and an analysis of the results are presented. Finally, the conclusions of the study are drawn in Sec. 5.

2. Description of the master module

Based on SDP, the master module has a 1-year planning period with weekly time steps and its state variables are: stored volume of water in the reservoir at the beginning of each week, weekly water inflow, and average weekly energy price. According to the findings of Goulter and Tai [14], the former variable is discretised in 9 equidistant values from the dead volume to the maximum one. The two latter variables are modelled by means of Markov chains following the approaches of Little [15] and Gjelsvik et al. [16], respectively. The order of the Markov chains was selected through the Akaike information criterion [17]. The number of classes of water inflows (5) and energy prices (3) were determined following the recommendation of Nandalal and Bogardi [11], and according to the length of the available historical series of these variables. As suggested by Kim and Palmer [18], the weekly extreme values of both variables were represented by their respective extreme classes in order to improve the robustness of the plant operation.

The master module uses the volume released from reservoir throughout each week as decision variable [11] and its objective function is:

$$Z_k^{i,a,b} = \max\left\{ z_k^{i,a,b,l} + \sum_x \left[\varepsilon_k^{a,x} \cdot \sum_y \left(\varepsilon_k^{b,y} \cdot Z_{k+1}^{l,x,y} \right) \right] \right\}; \forall \{a,b,i,l,x,y\} \in \Omega_k \wedge \forall k \in K$$

3. Description of the slave module

Based on MILP, the slave has a 1-week planning period with hourly time steps. The weekly evaporation rates and hourly water inflows and energy prices are input variables of the slave module. The disaggregations of these two latter variables from the weekly values considered in the Markov chains of the master module to hourly ones were performed by adjusting the average profile of every week of every variable to its considered value in its respective chain.

The slave module uses the flow released from the reservoir as decision variable and its objective function is:

$$\max\left\{\sum_{t\in T}\left(\pi_t \cdot p_t\right)-\sum_{t=2}^{168}\left[\alpha\cdot\left(p_t^{inc}+p_t^{dec}\right)+\beta\cdot\sum_{u\in U}\left(on_t^u+off_t^u\right)+\gamma\cdot\left(qos_t^{inc}+qos_t^{dec}\right)\right]+\sum_{j\in J}\left(vwv^j\cdot WV_k^{j,a,b}\right)\right\};$$
$$\forall\{a,b\}\in\Omega_k \wedge \forall k\in K$$

α and β can be estimated either by means of specific experimental studies in the considered plant or from the information contained in EPRI [19] and Nilsson and Sjelvgren [20], respectively, as it is done in this study. γ is a small (0.01) and artificial cost, neglected during the simulation, and considered in the slave module with the aim of obtaining a more realistic use of the bottom outlets and spillways.

The objective function of the slave module is subject to the following constraints: (1) initial stored volume; (2) water mass balance; (3) maximum legal storage capacities; (4) maximum technical storage capacity; (5) dead reservoir volume; (6) hourly evaporation losses; (7-13) use of the bottom outlets and the spillways; (14-16) maximum plant flow according to the stored volume and minimum technical stored volume for power generation; (17-20) power-discharge piecewise non-concave linear curve as in Conejo et al. [21], different as a function of the initial and estimated final stored volumes; (21) inter-hourly variation of the generated power; (22-26) start-ups and shut-downs of the hydro units; (27-30) expected revenue at the end of the week; and (31-32) up and down ρ. It is important to clarify that (14) has been added since the maximum plant flow may vary substantially within each week. The fulfillment of ρ between consecutive weeks is not considered and is one of the authors' ongoing works. The interested reader is referred to [Guisández et al., 2014] where the fulfillment of the interweek ρ was considered in a deterministic context.

$$v_0 = V_k^i; \forall i\in\Omega_k \wedge \forall k\in K \tag{1}$$

$$v_t = v_{t-1} + CF^1\cdot\left(w_t - e_t - q_t - qo_t - qs_t\right); \forall t\in T \tag{2}$$

$$v_{168} \le V_k^{legal}; \forall k\in K \tag{3}$$

$$v_t \le V^{\max}; \forall t\in T \tag{4}$$

$$v_t \ge V^{dead}; \forall t\in T \tag{5}$$

$$e_t = CF^2\cdot E_k\cdot\left(KE^1\cdot v_t + KE^2\right); \forall t\in T \wedge \forall k\in K \tag{6}$$

$$qos_t^{inc} - qos_t^{dec} = qo_{t+1} + qs_{t+1} - qo_t - qs_t; \forall t\in T \mid t<168 \tag{7}$$

$$qo_t \le KO^1\cdot v_t + KO^2; \forall t\in T \tag{8}$$

$$qs_t \le KS\cdot vas_t; \forall t\in T \tag{9}$$

$$v_t = vas_t + vbs_t; \forall t\in T \tag{10}$$

$$vbs_t \leq VS; \forall t \in T \tag{11}$$

$$sp_t \leq {vbs_t}/{VS}; \forall t \in T \tag{12}$$

$$vas_t \leq \left(V^{\max} - VS\right) \cdot sp_t; \forall t \in T \tag{13}$$

$$q_t \leq \sum_{c \in C} \left(Q^{\max,c} \cdot vq_t^c\right); \forall t \in T \tag{14}$$

$$v_t \geq \sum_{c \in C} \left(VQ^c \cdot vq_t^c\right); \forall t \in T \tag{15}$$

$$o_t^1 \leq vq_t^1; \forall t \in T \tag{16}$$

$$q_t = Q^{\min} \cdot o_t^1 + \sum_{s \in S} q_t^s; \forall t \in T \tag{17}$$

$$q_t^s \leq \begin{cases} e^s \cdot o_t^u; \forall s \in S \mid s^u \leq s \leq s^{u+1} \wedge u \in U \mid 1 \leq u \leq u^{\max} \\ e^s \cdot o_t^{u^{\max}}; \forall s \in S \mid s^u \geq s^{u^{\max}} \end{cases}; \forall t \in T \tag{18}$$

$$q_t^s \geq e^s \cdot o_t^u; \forall s \in S \mid s^{u-1} \leq s < s^u \wedge u \in U \mid u > 1; \forall t \in T \tag{19}$$

$$p_t = p^{\min} \cdot o_t^1 + \sum_{s \in S} \left(r^s \cdot q_t^s\right); \forall t \in T \tag{20}$$

$$p_t^{inc} - p_t^{dec} = p_{t+1} - p_t; \forall t \in T \mid t < 168 \tag{21}$$

$$q_t \geq Q^{\min} \cdot o_t^1 + \left(Q^1 - Q^{\min}\right) \cdot o_t^2 + \sum_{u=3}^{u^{\max}} \left[\left(Q^{u-1} - Q^{u-2}\right) \cdot o_t^u\right]; \forall t \in T \tag{22}$$

$$q_t \leq Q^{\min} \cdot o_t^1 + \sum_{u=2}^{u^{\max}-1} \left[\left(Q^u - Q^{u-1}\right) \cdot o_t^u\right] + \left(Q^{\max} - Q^{u^{\max}-1}\right) \cdot o_t^{u^{\max}}; \forall t \in T \tag{23}$$

$$on_{t+1}^u - off_{t+1}^u = o_{t+1}^u - o_t^u; \forall u \in U \wedge \forall t \in T \mid t < 168 \tag{24}$$

$$on_t^u + off_t^u \leq 1; \forall u \in U \wedge \forall t \in T \tag{25}$$

$$o_t^u \geq o_t^{u+1}; \forall u \in U \mid u < u^{\max} \wedge \forall t \in T \tag{26}$$

$$v_{168} = V^{dead} + \sum_{j \in J} vwv^j; \tag{27}$$

$$vwv^j \leq VWV^j \cdot wv^j; \forall j \in J \tag{28}$$

$$vwv^j \geq VWV^j \cdot wv^{j+1}; \forall j \in J \mid j < j^{\max} \tag{29}$$

$$wv^j \geq wv^{j+1}; \forall j \in J \mid j < j^{\max} \tag{30}$$

$$q_{t+1} + qo_{t+1} + qs_{t+1} - q_t - qo_t - qs_t \leq RR^{up}; \forall t \in T \mid t < 168 \tag{31}$$

$$q_{t+1} + qo_{t+1} + qs_{t+1} - q_t - qo_t - qs_t \geq -RR^{down}; \forall t \in T \mid t < 168 \tag{32}$$

4. Case study and main results

A Spanish hydropower plant was used to study the effects of the ρ on its water values. The plant is a dam-based scheme; the power house is located at the toe of the dam and the water is conveyed to the turbines via three different penstocks that go through the body of the dam. The technical data of this plant were provided by the power plant owner. The historical series of water inflows and hourly energy prices were taken, respectively, from the web pages of the Centre for Public Works Studies and Experimentation [22] (years: 1963-1965, 1966-2005) and of the Iberian Electricity Market Operator [23] (years: 1998-2005). The weekly evaporation rates were estimated thanks to the application of the empirical temperature-based formula proposed in Dragoni and Valigi [24] and of the average monthly temperatures taken from the web page of Spanish Statistical Office [25] (years: 1931-1960). The considered values of ρ, expressed as the number of hours necessary for the hydropower plant to "go" from standstill to maximum flow (or vice versa) at a rate equal to the average of the up and down ρ [26], are: 0h, 6h, 12h, 24h, 36h, 48h, 60h (magnitude proposed by the river basin authority) and 72h. The main design parameters of the hydropower plant are included in Table 1 and the average weekly water inflows and energy prices are depicted in Fig. 1.

Table 1. Main design parameters of the hydropower plant.

Main design parameter	Value	Unit
Max. legal storage capacity (15th Oct.-15th Apr.)	607.6	Mm^3
Max. legal storage capacity (16th Apr.-14th Oct.)	644.6	Mm^3
Max. technical storage capacity	654.1	Mm^3
Min. technical volume for power generation	71.0	Mm^3
Dead reservoir volume	48.1	Mm^3
Max. net head	132	m
Min. net head	72	m
Hydro units	3	Francis
Max. plant flow	279	m^3/s
Min. hydro unit flow	40	m^3/s
Max. power output	312.5	MW
Min. power output	22.2	MW

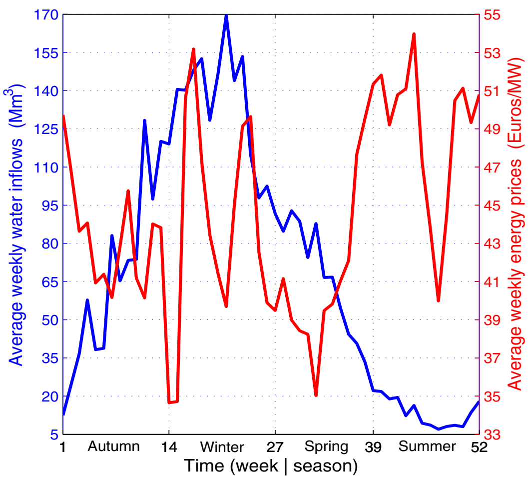

Fig. 1. Average weekly water inflows and energy prices.

In Fig. 2, the level curves of the obtained water values according to the stored volume across the year for 4 different values of ρ (0h; 24h; 48h; 72h) are represented. As it can be observed in this figure, the evolution of the water values is quite similar in all scenarios and consistent with Table 1 and Fig. 1: on the one hand, the lowest average absolute values appear in winter and the highest ones in summer, and, on the other hand, the lowest relative values of each week are given at the maximum stored volumes in winter whereas these ones during summer are located in the minimum stored volumes because of the lack of risk of spillages; the water values in summer are strongly influenced by the plant generation characteristic.

The averages across the stored volumes and the weeks of the water values have been included in Fig. 3 for every considered ρ, in relative terms with respect to the scenario without ρ. This figure reveals, among other things, that the effect of ρ on the reduction of the water values follows an approximate quadratic behaviour, almost 7% being the decrease in the water value in the scenario proposed by the river basin authority of the considered case study. It also shows that the reduction in the water value is nearly 3 times greater during the spring and the summer than in the autumn and in the winter.

5. Conclusions

This paper has presented a study on the influence of the maximum ramping rates on the water values of a real hydropower plant. For this purpose, a master-slave algorithm, based on stochastic dynamic programming and mixed integer linear programming, has been developed.

The obtained results of the case study seem to indicate that the water values are very sensitive to the presence of maximum ramping rates, as well as their magnitudes. Moreover, it has been observed that the above-mentioned sensitivity follows a quadratic evolution as the severity of the ramping rates increase. Finally, it has been detected that the impact of this environmental constraint on the water values is considerably higher during the months of low water inflows than during the ones of high water inflows.

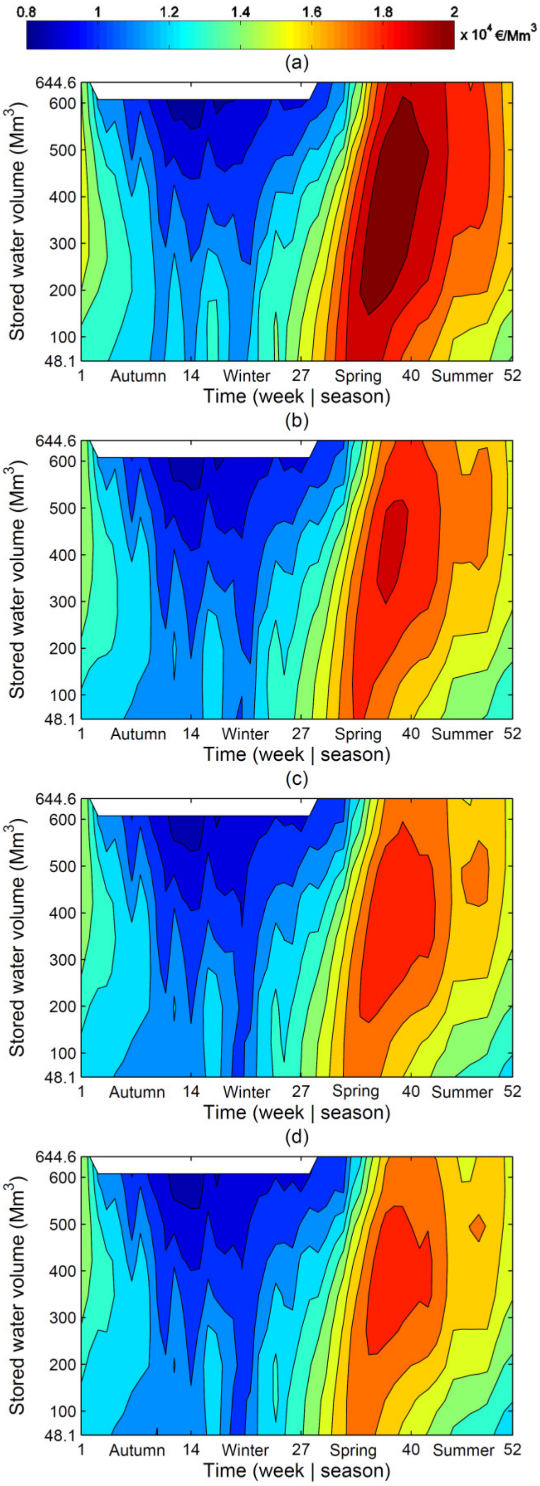

Fig. 2. Water value level curves with ρ = (a) 0h; (b) 24h; (c) 48h; (d) 72h.

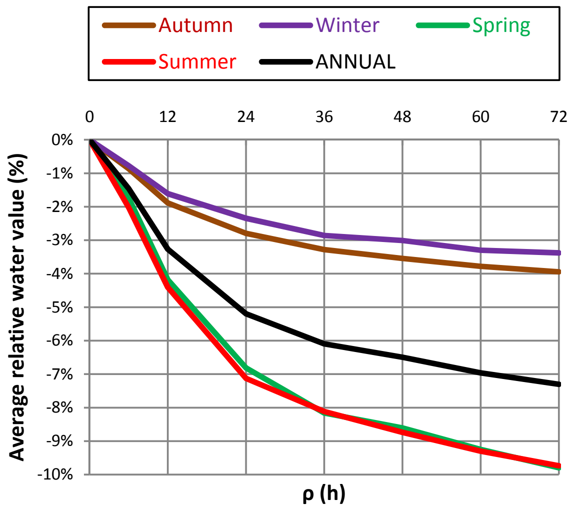

Fig. 3. Average annual and seasonal relative water values according to ρ.

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